Stressed Skin Construction in the UK

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1. Introduction

Interest in stressed skin construction in the U.K. was aroused in the mid 1950's when tests on a number of complete, clad, steel framed structures revealed that the measured stresses and deflections were significantly less than those predicted by the design calculations[eg 1]. Typically, these structures were warehouse or workshop buildings with no internal floors or partitions so that the only explanation available was that the cladding (corrugated steel or asbestos sheet) was assisting the frames to carry the loads.

This prompted the first author in the early 1960's to initiate a program of research to quantify this effect with a view to its incorporation in design calculations. In the years that have elapsed, the fundamental principles of the stiffening effect of cladding have been elucidated and incorporated in the first book on the subject[2].

Initially, interest concentrated on utilising and, if economically possible, enhancing the action present in structures constructed according to conventional British practice. A fundamental concept in this work has been the individual panel or diaphragm shown in Fig 1. Of note is the fact that all of the connections shown are made with discrete fasteners such as self tapping screws, blind rivets or fired pins. Site welding of secondary framing and cladding is quite unknown in the U.K.

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The manner in which the series of diaphragms formed by the roof cladding and its supporting members stiffens a typical pitched-roof framed structure is illustrated in Fig 2. The cladding acts in a manner similar to a deep plate girder carrying a proportion of the imposed load back to the comparatively rigid gables. The purlins act as flanges carrying the axial forces due to bending action and the sheeting acts as the web carrying the shear force. Clearly the purlin connections must allow the transmission of axial tensions and compressions though, because of the considerable depth of the assembly, these are not large. At the same time the gables, either as a consequence of their own cladding or additional bracing members, must be sufficiently stiff and strong to provide a load path to the foundations for the shear force.

As the practical exploitation of diaphragm action became possible it became clear that a major application was going to be, not in assisting rigid-jointed frames to carry load, but rather in stabilising nominally pin-jointed frames. In flat roof construction, the lateral loads on the structure generally appear at eaves level in the plane of the diaphragms. Diaphragms are particularly efficient in resisting this form of loading and the necessity for either wind bracing or rigid joints can be removed as illustrated in Fig 3. It will be shown in section 4 that the practical exploitation of diaphragm action in the U.K. to date has been concentrated in this form of stressed skin action though this may be partly a consequence of the position regarding British Standards and Codes of Practice.

A logical extension of this work involves discretely fastened folded plate structures. Much work has already been done in developing the theory[3,4] but only one such structure has been built in the U.K. to date. This was fully tested under the supervision of a team from the University of Salford and is described in section 4.

2. Standards and Codes of Practice

At the time of writing, the utilisation of diaphragm action has been inhibited as it has not been permitted by the current regulations governing structural steelwork in the U.K.[5]. This has effectively limited the use of diaphragm action to either schools and other public buildings which are subject to somewhat different regulations from buildings in general, or to structures sufficiently large to justify the application for and granting of a special waiver to permit stressed skin construction.

It is anticipated that this situation will shortly undergo a dramatic change with the release of a new British Standard for structural steelwork and European Recommendations for Stressed Skin Construction[6]. It is expected that both of the above documents will draw a clear distinction between the two forms of stressed skin action referred to above, namely

(1) The use of diaphragm action to stabilise nominally pin-jointed structures

(2) The use of diaphragm action to provide further economies in rigid-jointed framed construction.

In the process of considering the above documents, a number of basic principles for stressed skin construction have been enumerated, the most important of which may be summarised as follows:-

(a) Suitable connections must be provided in order to transmit the forces arising from diaphragm action to the main structural framework and, at suitable points, to the foundations.

(b) Diaphragm action should normally be utilised primarily to carry loads which are themselves applied by the sheeting, eg wind and snow loads. Other short term transient loads, eg surge forces from light overhead cranes, may also be carried.

(c) Fasteners connecting the sheeting to the supporting structure and fasteners forming seams between adjacent sheets should be of a type which will not work loose in service nor fail prematurely before causing tearing of the cladding material.

(d) Openings for roof lights or other purposes must be restricted as far as both area and position are concerned. Current thinking suggests an upper limit of 15% of the area of a given diaphragm provided that a random pattern of openings is used.

(e) Diaphragms should be designed in such a way that the failure mode is ductile. This will normally involve designing for failure of the sheeting at the seam or sheet/shear connector fasteners and ensuring a greater reserve of safety for other modes. The current suggestion is that other failure modes, particularly those involving buckling of the sheeting or failure of the sheet/purlin fasteners in lateral shear, should have a 25% greater reserve of safety.

(f) If the principle suggested in (e) above is followed, there is no need to consider the interaction between diaphragm shear loading and normal loading due to wind or snow. The fasteners that are the failure criterion in shear carry only nominal forces due to normal load. In fact, there is no evidence for any significant interaction when other failure modes are considered but (c) and (f) together appear to provide a logical and safe approach.

(g) With nominally pin jointed structures (type 1 above) the diaphragms provide the entire stability of the structure and the inadvertent removal of a portion of the roof sheeting could prove catastrophic. For this reason, stressed-skin structures of this type must be provided with prominent identifying notices.

(h) With rigid-jointed structures (type 2 above) identifying notices are not necessary provided that the bare frames are just stable in the absence of the cladding though with a much reduced reserve of safety. A typical requirement is that, for frames designed elastically, the bare frames may be stressed to the yield point in the absence of the cladding or that, for frames designed plastically, the bare frames may have a load factor of not less than 1.1.

(i) It should also be noted that in a typical diaphragm the shear stress in the sheeting is only likely to be a small fraction of the bending stress due to normal loading. Consequently, in the event of corrosion of the sheeting, the sheeting will fail in bending long before the stressed skin action is impaired. It is advantageous to formally recognise this state of affairs and to fix an upper limit to the average shear stress in the sheeting at, say, 25% of the permissible bending stress.

3. The Design of Individual Diaphragms

Diaphragms must be divided into two basic types depending on whether the sheeting is fastened to the supporting structure on all four sides (direct shear transfer) or just at the ends of the sheet (indirect shear transfer). The usual way of obtaining direct shear transfer involves the use of shear connectors as shown in Fig 1. These are usually purlin offcuts and their use allows the purlin/rafter connections to be greatly simplified. Diaphragms with direct shear transfer are usually appreciably stiffer and stronger than diaphragms with indirect shear transfer and therefore fastening on all four sides is recommended though not mandatory.

Diaphragms must be further subdivided into 'simple' and 'complex' types. Simple diaphragms are rectangular in plan, regular in construction and contain no large openings. They may be designed by simple methods such as that described for diaphragms with direct shear transfer in reference 7.

Simple diaphragms with indirect shear transfer have caused difficulties in the past as the internal force distribution was conjectural. Recent work utilising finite element techniques has clarified this problem[8] and simple and reliable methods are now available for this case also.

Complex diaphragms, which are of irregular shape or contain large openings, cannot be designed by simple methods. They therefore require testing or comprehensive analysis using recently developed finite element techniques[8,9].

4. Stressed Skin Buildings in the U.K.

During the past few years a large number of stressed skin buildings have been erected in the U.K.. In almost every case the stressed skin element has been the roof deck which has been used as a diaphragm to resist the horizontal wind loads. The buildings range from a large commercial and an industrial building to a wide variety of public buildings, including schools, colleges, libraries, police headquarters and computer buildings. The few instances where pitched or hipped roofs have been used in stressed skin designs include a range of nursery schools.

Notable or typical examples from these buildings will now be described in greater detail.

4.1 Fruit and Vegetable Building - New Covent Garden Market

This market has recently been built on the south bank of the River Thames in London and replaces an old market which stood for 300 years in central London. A general description of the new market is given in reference 10 from which Figures 4 and 5 have been taken.

The building consists of twin structures each 386m long and 65.6m wide, linked by two amenity bridges. The roof deck was designed as a horizontal diaphragm spanning between the transverse fire walls seen in Fig 4, so that it carried the wind load on the side of the building back to these walls. Typical sections through one of the twin buildings are shown in Fig 5. Individual roof deck diaphragms were about 52m long and of various widths above 20m.

Because of the high wind force and the need to limit the deflection at the centre of length of the deck, it was necessary to fasten the deck in every corrugation and to use seam fasteners at close centres. Also, because the decking was fastened to the purlins only, it was necessary to check the strength and flexibility of the purlin/rafter connections.

As a result of using the roof deck as a diaphragm, horizontal wind bracing in the plane of the roof was eliminated and steelwork details standardized. The consultants found the construction economical despite the additional fixings.

4.2 Public Building Systems

There are, in the U. K. , a number of building systems used by counties, cities, universities and government departments for the construction of public buildings. Several of these, including CLASP (Consortium of Local Authorities' Special Programme), SEAC (South Eastern Architects' Collaboration) and SCOLA (Second Consortium of Local Authorities) use the steel roof deck as a diaphragm.

Since it was impractical to carry out a detailed design of the roof deck for each individual building, a simplified method was prepared, using tables and graphs, so that architects could easily check whether a particular roof deck would be strong and stiff enough to act as a horizontal diaphragm.

For SEAC the specification for the decking was as follows:-

Deck: 38mm deep, 1.8m span, fastened to the purlins only

Fasteners: every corrugation at the sheet ends and alternate corrugations at the intermediate beams

Seam fasteners: two different specifications (1) standard (2) high wind

Deflection: not greater than height of building/500

Load factor: 1.7 for wind

Using the above data, Webb[11] calculated the strength and deflection of 60 different sizes of roof decks. As a result of this, he found that for this particular system simple relationships existed between the strength and width of the diaphragm, and between the deflection and width of the diaphragm. Simple charts were then prepared from which the width of deck required for any length and loading could be read off. This procedure was also followed by CLASP. The resulting method has been published in a brochure[12].

The above simple design process was checked by carrying out shear tests on full size panels of SEAC and CLASP roof decks at the University of Salford. Fig 6 is typical of these, while Fig 7 shows a deck under simultaneous shear and upward load (to simulate wind suction). Fig 8 shows a test on a deck with openings to simulate roof lights. The findings of these tests are reported in reference 12.

Views of a typical CLASP building, the Computer Building, County Hall, Nottingham, during erection and after completion, are shown in Figs 9 and 10. Another CLASP building, Dalestorth Primary School[13] is shown in Figs 11 and 12.

Although it is difficult to give an overall figure for the economies made by using roof decks as diaphragms in the above buildings, it has been estimated that elimination of the horizontal wind bracing in the plane of the roof has saved 6.5 percent of the frame cost. Other indirect savings which are probably at least as significant are due to the fact that

(1) the details of all frames are now similar and fewer different components are required within each system

and (2) because pinjointed frames can be used, foundation costs may be reduced.

4.3 Tablet Factory at Nottingham

This factory for the Boots Company Ltd is shown in Fig 13. Again, the roof deck was designed as a horizontal diaphragm, carrying the wind on each side of the building.

The data for the deck were as follows:-

Deck: 48mm deep, beam spacing 3m, fasteners on all four edges

Sheet/purlin fasteners: cartridge fired pins at alternate 150 and 300mm spacings

Sheet/rafter fasteners: cartridge fired pins at 750mm centres

Seam fasteners: self drilling/tapping screws and stainless steel pop rivets at 430mm

Fig 14 shows the roof deck during erection.

In the design process, wind from the West was first considered and the shear force across the full deck was found (Fig 15). This shear was then divided between the lines of roof decks, in proportion to their shear stiffnesses which are in turn proportional to their widths (Fig 16). The worst shear in a panel was found (ie panel shaded), and the fasteners in this panel were designed to take this shear with an adequate load factor. This method of analysis, although approximate, was conservative. Moreover, if a line of roof deck was removed for maintenance purposes, it allowed a check to be made on the remaining lines, using a slightly reduced load factor, so that instructions could be given as to how much roofing could be removed at once. Similarly, wind from the North was considered, and the roof again divided into lines. The critical panel was again taken as the criterion of design.

4.4 MACE Nursery School

A rather different form of stressed skin design has been used in these system built schools designed by the Metropolitan Architectural Consortium for Education[14]. The light steel framework, comprised primarily of rectangular hollow sections, is propped during erection (Fig 17) and then the roof is sheeted with 80 mm deep x 0.7 mm thick galvanised steel decking (Fig 18) which is subsequently insulated with fibreboard and then felted. There is a roof light at the centre of the roof, so that the roof forms a truncated pyramid.

If the roof load were perfectly symmetrical and concentrated at the four corners of the roof light, there would be no shear load in the sheeting. In fact, because the roof load can be unsymmetrical and is distributed, and because the roof must also be designed for horizontal wind load, the sheeting acts as an inclined shear diaphragm. Because of the novel design, tests were required by local authority (Fig 19) to ensure that the strength and stiffness of the structure met the requirements of the Code of Practice. In fact, the behaviour of the structure was quite satisfactory and a range of nursery schools of this type are being designed and built.

It is hoped that these examples give an indication of the extent to which stressed skin design is being used in the U.K. It should be noted, that of all the buildings erected on this method of design, so far as is known, not one has given rise to any difficulties on site or in subsequent service.

5. The Use of Diaphragm Action to Provide Economy in the Design of Rigid-Jointed Frames

When diaphragms act in conjunction with rigid jointed frames there are two alternative load paths and the load is shared between the diaphragm assembly and the frames according to their relative stiffnesses. This leads to problems which are essentially analytical as it is no longer possible to consider the diaphragms and plane frames independently.

Initially, this three-dimensional situation was made managable for manual analysis by the preparation of design tables[2]. Once the stiffness ratio between frames and diaphragms was determined, the load ratios for the individual frames could be read directly from the tables. On the basis of this approach, several full scale tests were carried out[15,16,17] and the assumed interaction was verified conclusively.

The manual approach suffered from the disadvantage that it could only be applied to regular single-bay structures subject to uniform loading. For this reason a computer analysis was developed and it was found that the full three-dimensional behaviour could be reproduced using a conventional plane frame analysis program[18]. This possibility exists because the shear stiffness of a complete diaphragm can be summarised by a single quantity (the reciprocal of the flexibility 'c' in reference 5) and therefore the analysis of a complete structure such as that shown in Fig 2 can be simplified to the equivalent structure shown in Fig 20.

In Fig 20 the frames are shown slightly apart for clarity. There is no reason why they should not be coincident whereupon the complete structure has reduced to an unusual plane frame. Conventional programs can readily handle coincident members and joints and the 'springs' can be simulated by prismatic members of appropriate cross-sectional area and Young's modulus and zero second moment of area.

The above approach offers an analysis of a complete clad structure. For design it is necessary to proceed iteratively from an estimated starting point. A suitable starting point usually involves bare frames designed to a reduced load factor (see section 2(h)) and diaphragms calculated on the basis of the minimum number of fasteners. After an initial analysis, this design can be modified, if necessary, to accommodate the calculated frame moments and diaphragm forces and a second analysis carried out.

This process can be continued until both the frame stresses and diaphragm shears are within permissible limits. This involves the achievement of a stiffness balance between the frames and diaphragms that is compatible with their relative strengths. This does not usually present any problems. Convergence is rapid, two or three cycles of iteration normally being sufficient to obtain a satisfactory design.

The structures under discussion are of a type that are more frequently designed by plastic rather than elastic methods. It has been shown(19) that plastic design of stressed skin structures is permissible provided that:-

(a) The diaphragms are designed for ductile failure as discussed in 2(e)

(b) A serviceability check is incorporated. On the basis of an elastic analysis the diaphragms must not be subject to yield at the working loads.

The plastic design of stressed skin structures requires a viable plastic analysis. A manual analysis can be readily carried out for simple structures that are within the scope of a manual elastic analysis(19). For more complex cases, a computer analysis is required. Such an analysis is available(19), being similar in basis to the elastic analysis described above but incorporating plastic hinge action in the frames and compressive or tensile yield of the 'springs' simulating diaphragms. Again, the design has to proceed iteratively and converges rapidly to an acceptable design. It may be observed that the requirements for stiffness balance are less onerous than in the corresponding elastic design involving only the satisfaction of the serviceability requirement (b) above.

An attractive possibility, currently being developed by the second author at the University of Salford, involves the automatic computer-aided design of rigid-jointed framed structures incorporating diaphragm action. In the current state of development, it is necessary to input the diaphragm strength and stiffness together with the usual details of the frame geometry and loading. The program then enables a design for member sizes to be obtained together with an elastic analysis of the designed structure at the working loads. Thus, the check for serviceability and any necessary adjustment of the diaphragm design must be carried out manually and a rerun of the program may be necessary.

The basis of this work is a problem-orientated, near-minimum weight design technique[20] that has proved to be a most efficient means of designing plane frames and is finding increasing commercial usage.

It may be appreciated that, although extensive testing of complete structures involving rigid-jointed frames and diaphragm action has been carried out, no actual structures designed on this basis are known to the authors. It is hoped that this state of affairs will be changed with the publication of the new British Standard for Structural Steelwork and the more ready availability of the computer programs described above.

6. Current and Future Developments

Clearly, much of the future of stressed-skin construction in the U.K. depends on the incorporation of the relevant clauses in the appropriate British Standard. If, as seems likely, this is implemented within the near future the way will be open for increasing utilisation of stressed skin principles. The inclusion of a new concept in a British Standard implies in itself a high level of acceptance by the profession and this can only increase with increasing experience of the ideas in practice.

Research in this field in the U. K. is concentrated at the University of Salford and various topics are under active consideration. Among these are the following:-

(a) Simple methods for the design of diaphragms with large openings and other effects that are, as yet, out with the simple treatment described in Reference 7. Included in this work is an approximate rapid treatment of certain types of diaphragms based on a series of safe assumptions.

(b) Non-linear computer analysis of diaphragms leading to an improved understanding of internal force redistribution and modes of failure.

(c) Folded plate construction with discrete fasteners culminating in a full scale test of a 21.6 m span roof.

(d) The automatic design of rigid-jointed framed structures incorporating diaphragms.

(e) Various aspects of light gauge steel shell construction.

Each of these projects is being carried out with the practical requirements of industry in mind and, where possible, in direct consultation with industry.

7. Conclusions

The state of the art regarding stressed-skin construction in the U. K. has been described and current thinking regarding Codes of Practice outlined. A number of notable uses of diaphragm action have been described and it is expected that the utilisation of this method of construction will increase. Some topics currently under research and development are described.

8. Acknowledgements

The consulting engineers for the New Covent Garden Market were Clarke Nicholls and Marcel and the Tablet Factory for the Boots Company Ltd was designed by John Laing Design Associates Ltd.

Summary

The fundamental basis of all stressed skin construction is the design of individual shear diaphragms. In the U.K. this has followed a somewhat different course to that in the U.S.A. in that fastening techniques have invariably involved discrete fasteners such as self tapping screws, welding being virtually unknown, and research has concentrated on developing design by calculation without reliance on testing. In this paper the state of the art regarding diaphragm design is reviewed and some notable uses of diaphragm action in the U.K. are described. The position regarding codes of practice is also discussed.

The interaction of diaphragm action and rigid-jointed framed construction leads primarily to analytical problems. Procedures for the elastic and plastic analysis and design of such structures are described. Finally some current research trends are outlined.

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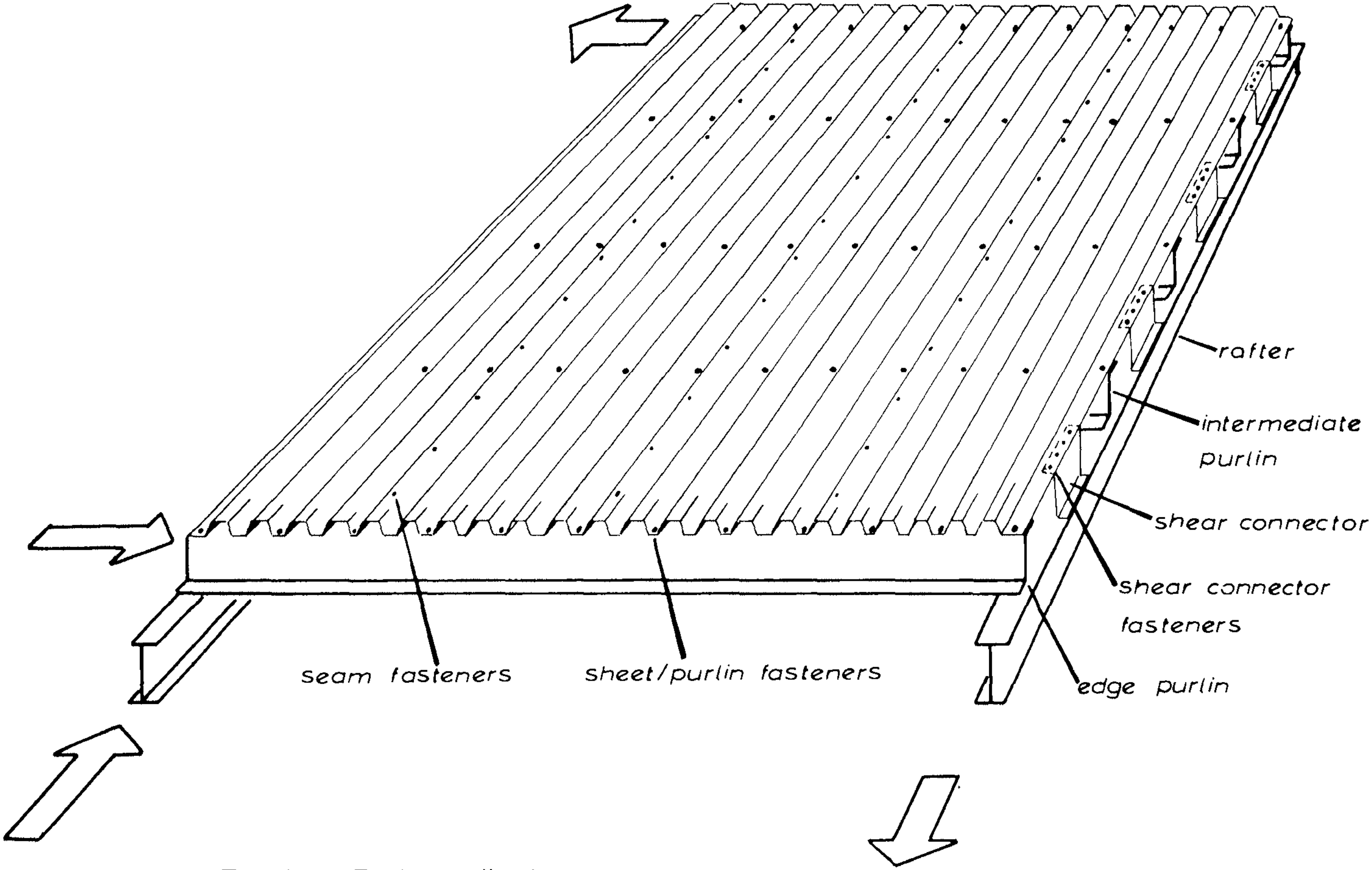


Fig 1 Typical diaphragm

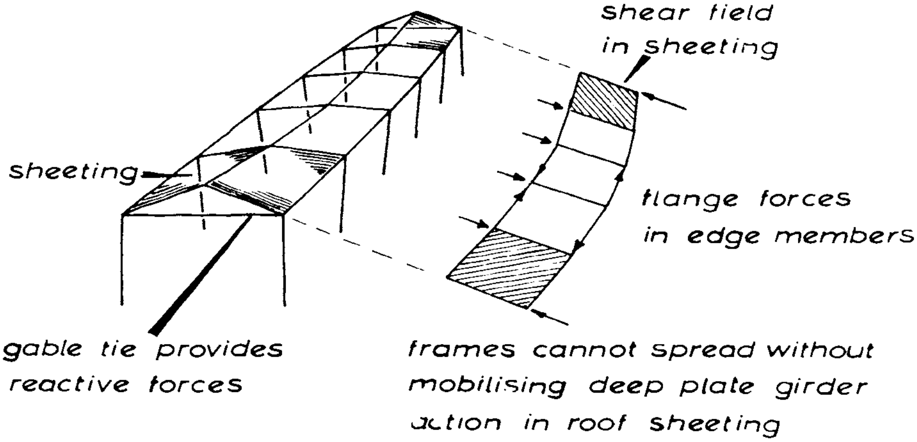


Fig 2 Diaphragm action in a rigid-jointed structure

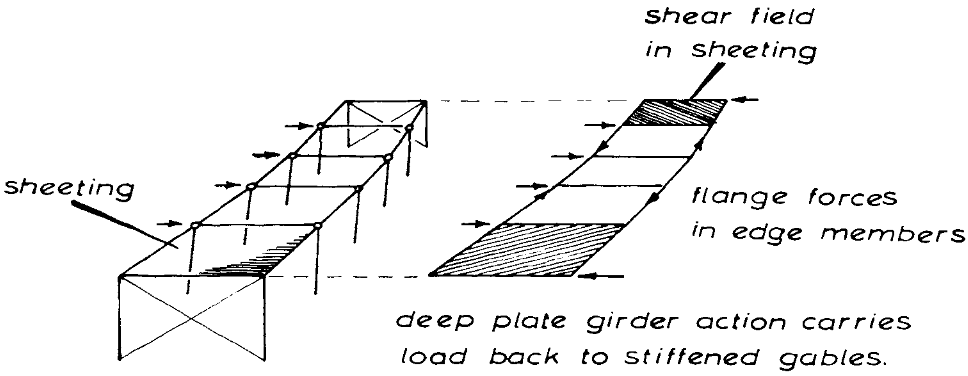


Fig 3 Diaphragm action in a pin-jointed structure

Fig 4 Aerial view of fruit and vegetable market

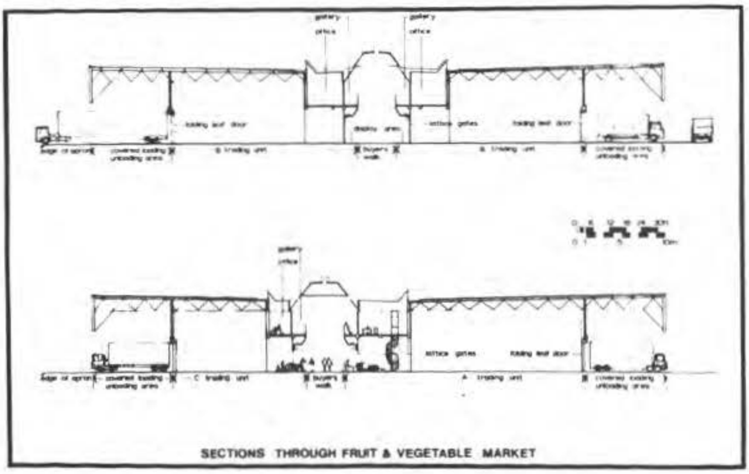


Fig 5 Sections through fruit and vegetable market

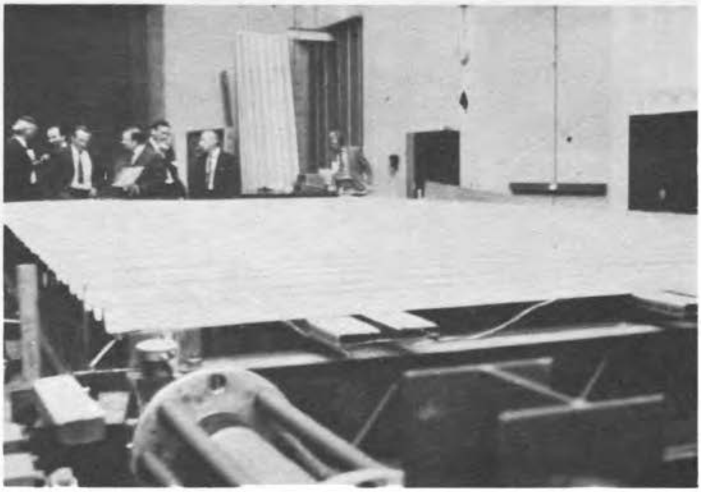


Fig 6 Shear test on a SEAC diaphragm

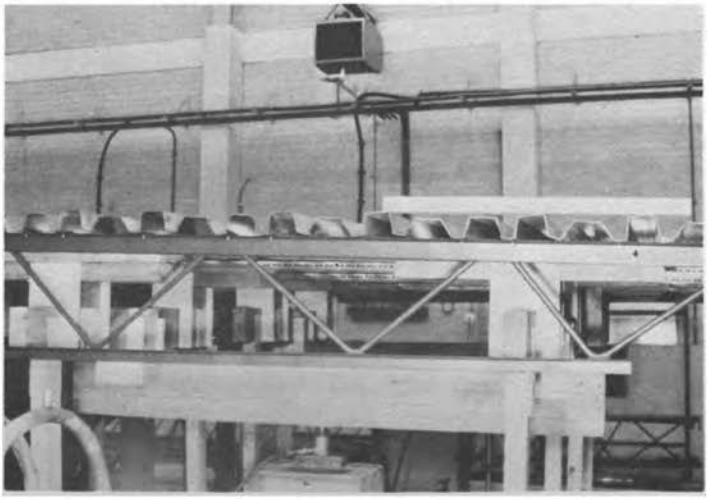


Fig 7 Diaphragm under shear and upward load

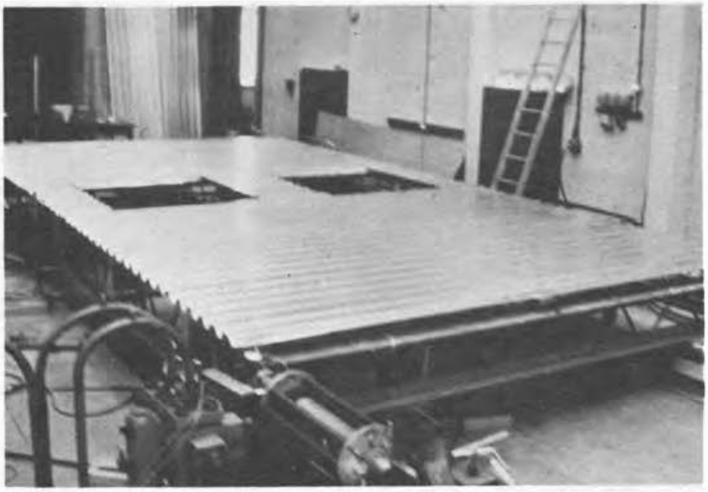


Fig 8 Shear test on diaphragm with openings

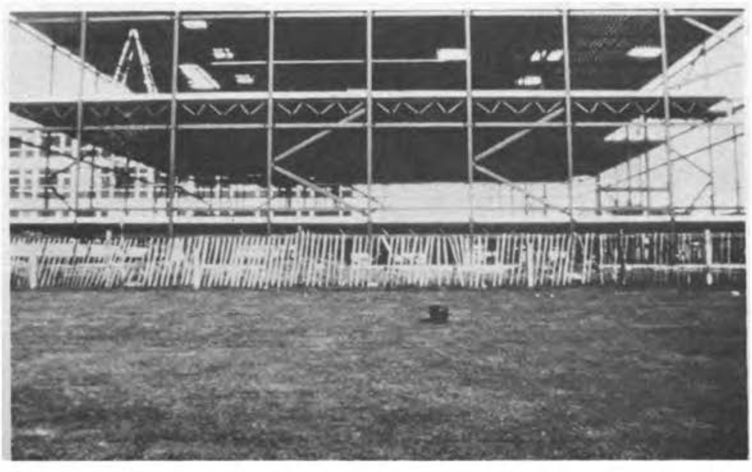


Fig 9 CLASP Computer building under erection

Fig 10 Completed computer building

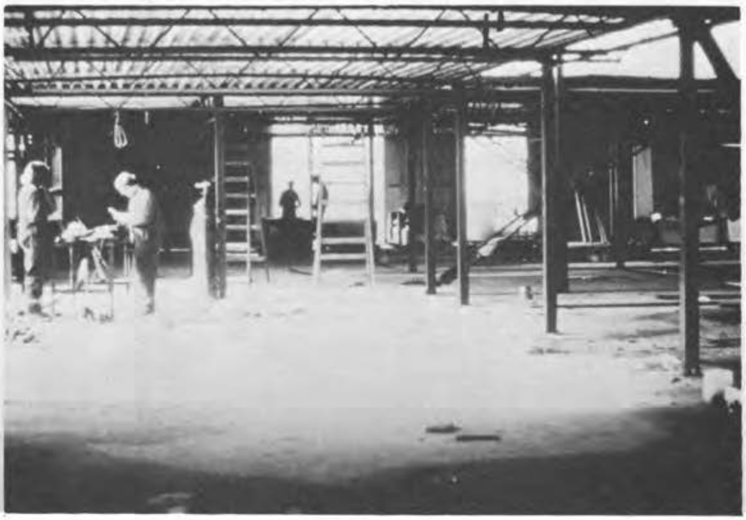


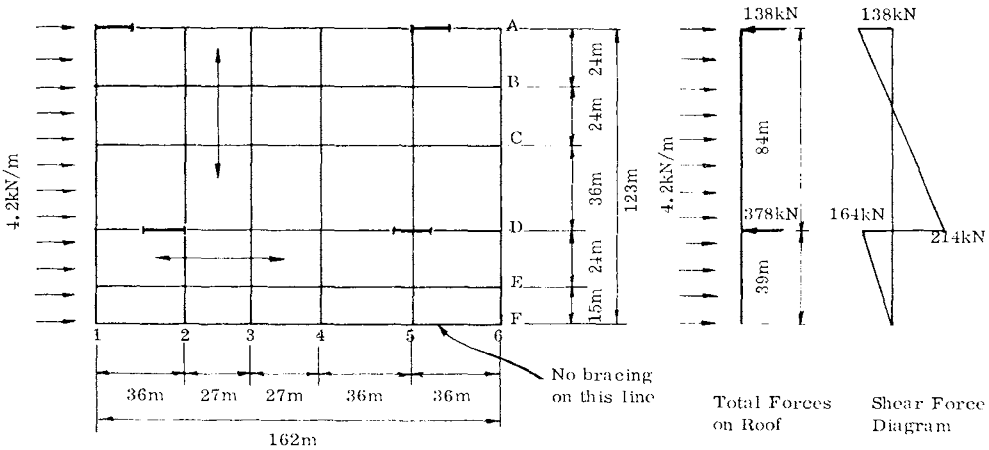
Fig 11 CLASP school under construction

Fig 12 Completed school building

Fig 13 General view of tablet factory

Fig 14 Roof deck under construction

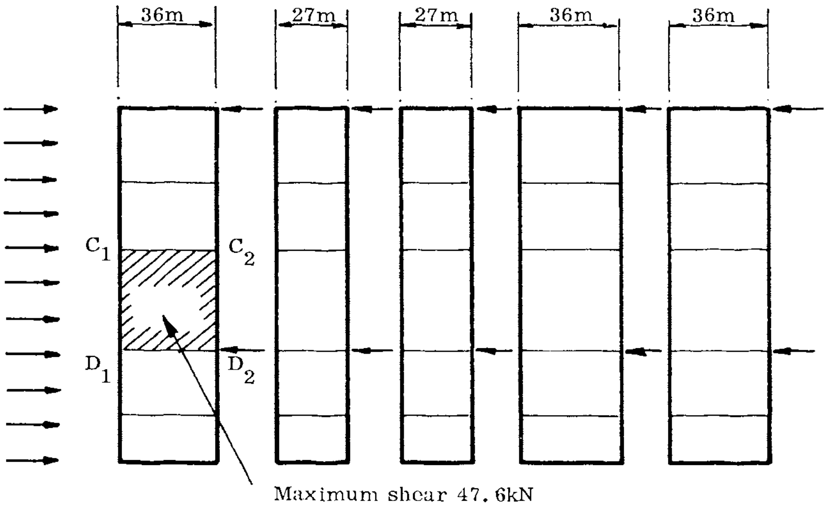
Wind from West



General Roof Plan Showing Vertical Bracing

Fig 15 Tablet Factory - design under wind from West

Wind from West



Exploded View of Roof Showing Subpanels

Fig 16 Tablet factory - sub-panels used in design

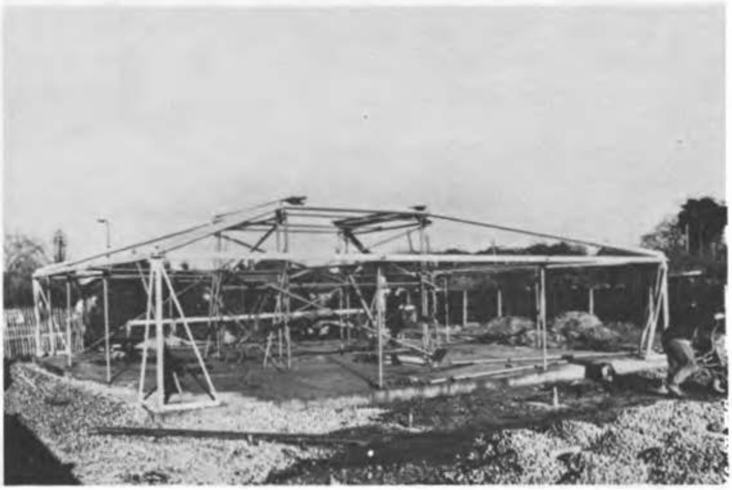


Fig 17 Erection of MACE nursery unit

Fig 18 Completed structure prior to test

Fig 19 Nursery unit subjected to combined vertical and side load

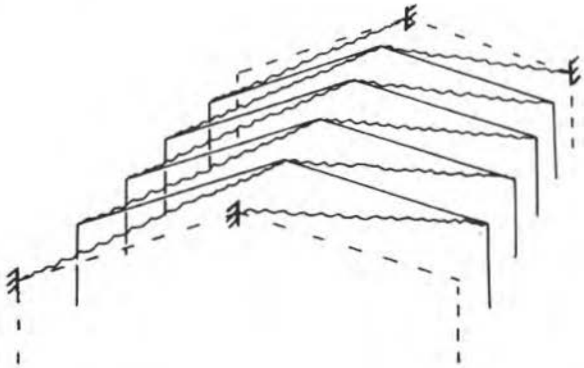


Fig 20 Equivalent structure for the computer analysis of a building with rigid-jointed frames.